Sec 2.7 Grossman-Nir violating models

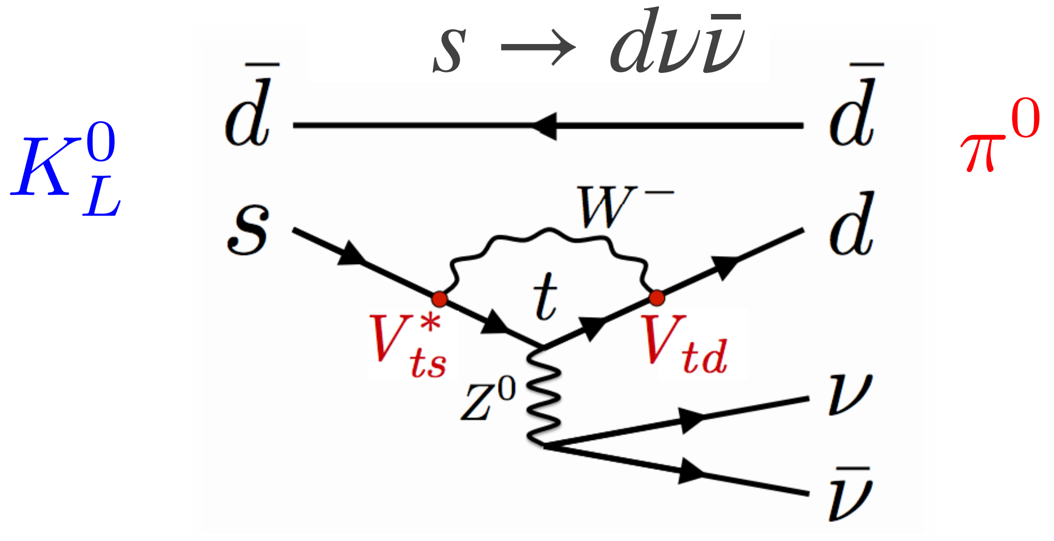
Yuval Grossman, Matheus Hostert, Teppei Kitahara, Maxim Pospelov

Zoom meeting “Searches for Hidden Sectors at Kaon and Hyperon Factories,”
January 22, 2021

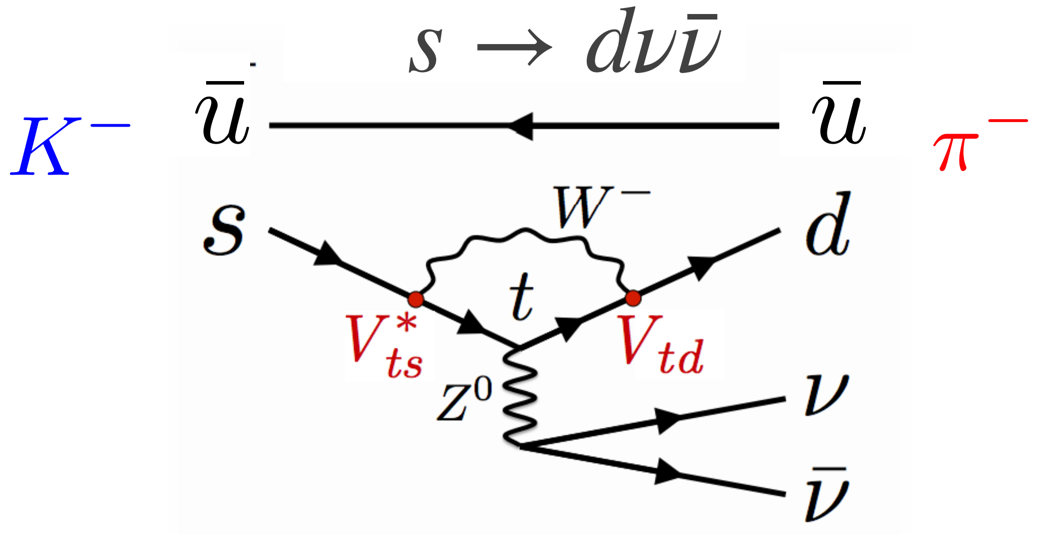
Teppei Kitahara (Nagoya University)

NAGOYA
UNIVERSITY

Grossman-Nir bound



Same diagram in quark level



$$\frac{\Gamma\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{\Gamma\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} = \frac{(\mathrm{Im}\, M)^2}{|M|^2} \leq 1$$ (Isospin relation $\Delta I = 1/2$)

◆ Grossman-Nir bound for general NP models (including $\nu_i \bar{\nu}_j$) [Grossman, Nir '97; Grossman, Isidori, Murayama '04]

$$\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(\frac{\tau_L}{\tau^+} + \Delta_{\text{IB, EM}}\right) \sin^2\theta \mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 4.32 \mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

◆ *e.g.*, Grossman-Nir bound can be applied for scalars channel

$$\theta = \mathrm{Arg}\left(\frac{q}{p} \frac{\langle \pi^0 \nu\bar{\nu} | \mathcal{H} | \bar{K}^0 \rangle}{\langle \pi^0 \nu\bar{\nu} | \mathcal{H} | \bar{K} \rangle}\right) / 2$$

$$\mathcal{B}\left(K_L \to \pi^0 X\right) \leq 4.32 \mathcal{B}\left(K^+ \to \pi^+ X\right)$$

The bound is saturated when X is CP-even scalar [Leutwyler, Shifman '90]

Grossman-Nir bound

- Is the Grossman-Nir bound strict one on general new physics scenario?
  - No! But, it is strict on many new physics cases.

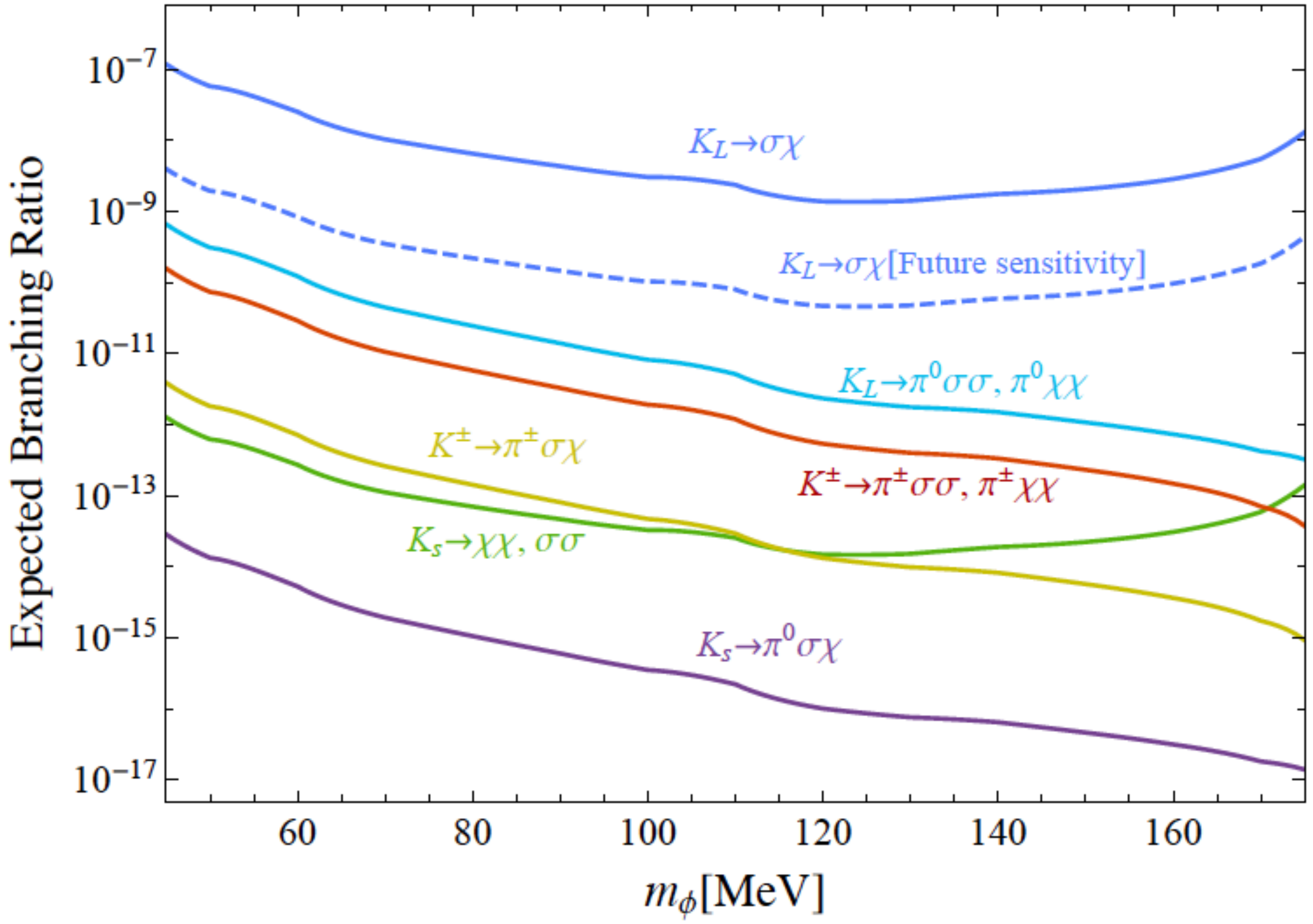
Violation of Grossman-Nir bound

- $\gamma\gamma$ (in K_L mode) comes from not π^0 but other sources
- Two dark particles; $X_2 \to X_1 + \pi^0$ [Section 2.8]
- Isospin-violating operator by dimension-seven interaction
- Kinematics (phase space difference; $m(K_L - \pi^0) = 362, m(K^+ - \pi^+) = 354$MeV) [backup slide]
- **Effective violation** of the Grossman-Nir bound (GN bound is satisfied in the parton level)
  - Detector size difference ("lifetime gap")
  - Pion-mass new physics ("π^0 blind spot") [backup slide]

$\gamma\gamma$ comes from not π^0

- $K_L \to \sigma^0\chi^0$, $\chi\to\gamma\gamma$ in strange flavor symmetry with ChPT (SM + ϕ; $\phi = \sigma + i\chi$; σ is stable within detectors) [Gori, Perez, Tobioka '20]
- This is annihilation of quark lines, and there is no counterpart in K^+ decay
- Note: there is also $K_L \to \pi^0\sigma\sigma$ and $K^+ \to \pi^+\sigma\sigma$ with the same small ratios
- Only $K_L \to \sigma^0\chi^0$ can be probed by KOTO

<Assuming 3 KOTO signals>

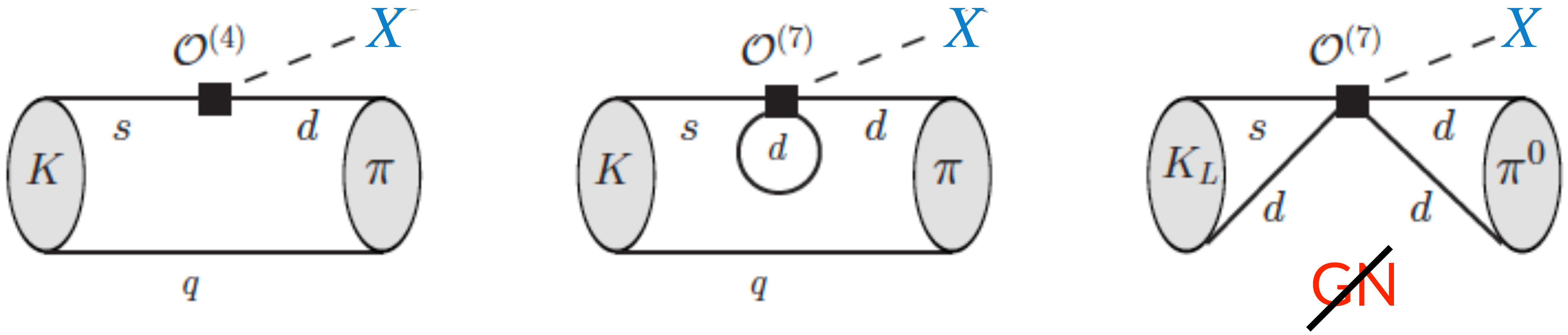


Assuming stat.= x30 in future

Isospin-violating operator

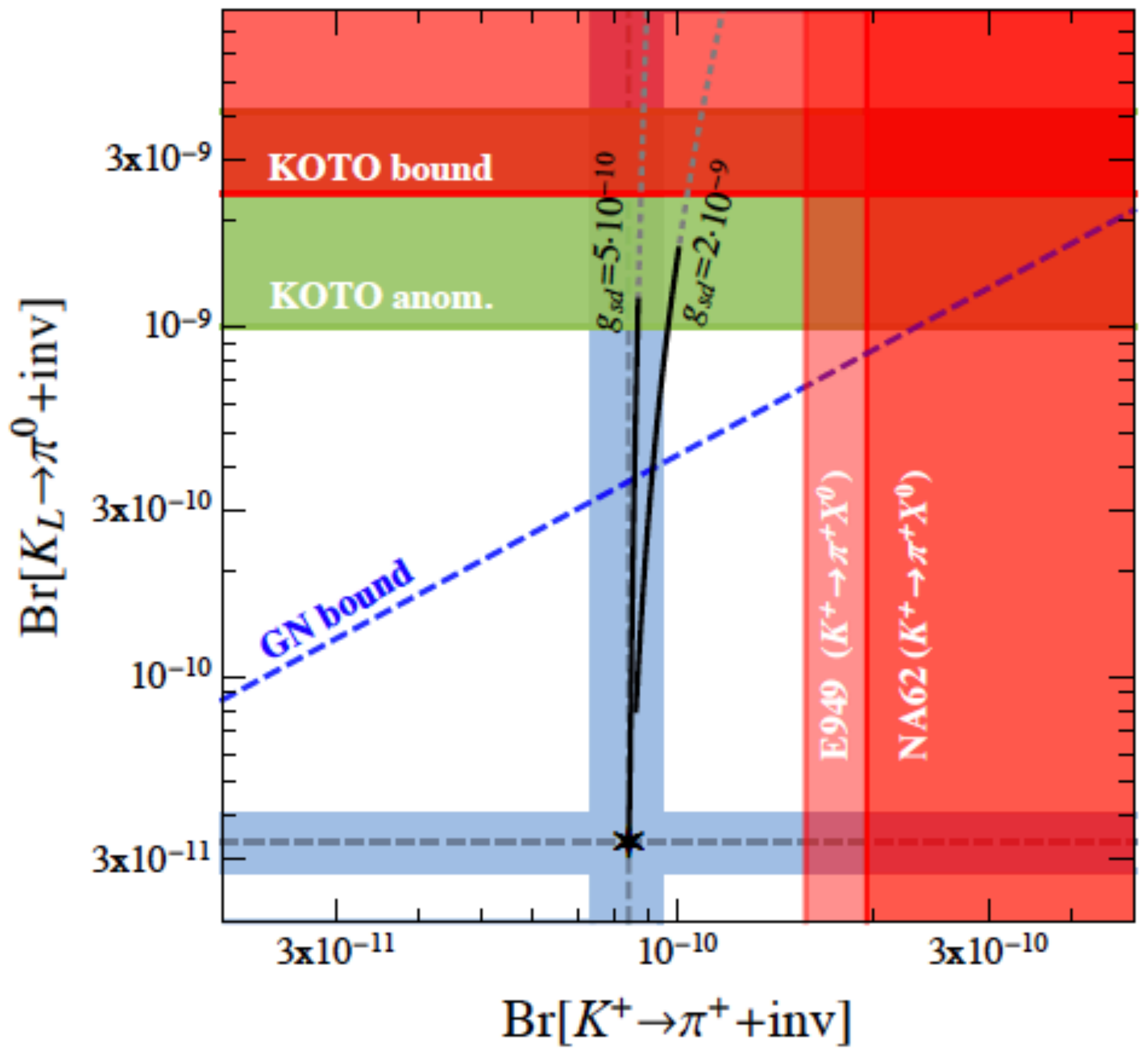
- The following isospin-violating operators can violate the Grossman-Nir bound [Ziegler,Zupan, Zwicky '20]

$$\mathcal{L} = c^{(4)}(\bar{s}d)X + \frac{c_i^{(7)}}{\Lambda^3}(\bar{s}\Gamma_i d)(\bar{d}\Gamma'_i d)\,X$$



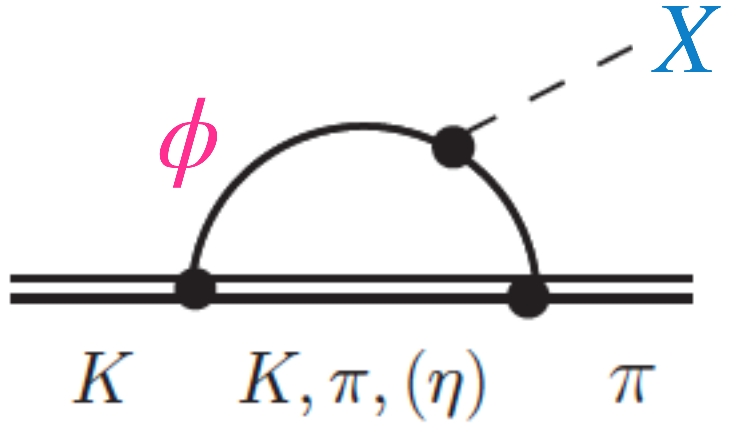
$c^{(4)} \ll c^{(7)}$ is required for large violation of the GN bound

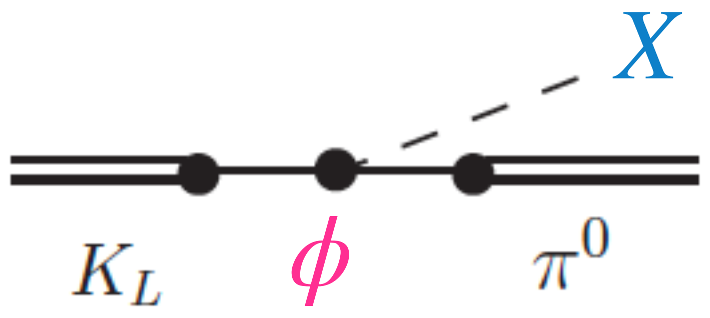
~~GN~~



- This structure is realized by additional $\mathcal{O}(1)$ GeV mediator ϕ

$$\mathcal{L} = g_{sd}(\bar{s}_L d_R)\phi + g_{dd}(\bar{d}_L d_R)\phi + \lambda m \phi^2 X$$

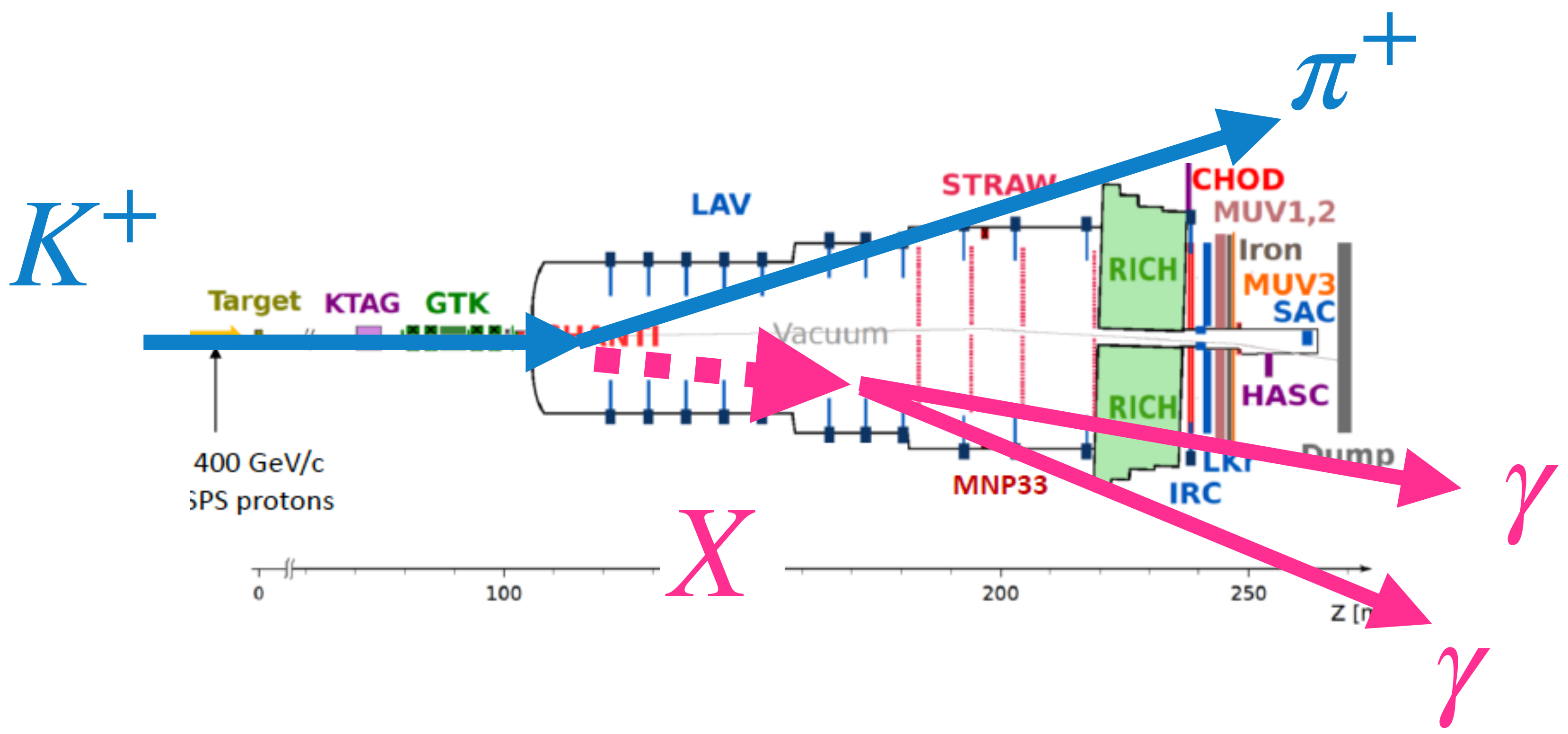




Effective violation of GN bound “lifetime gap”

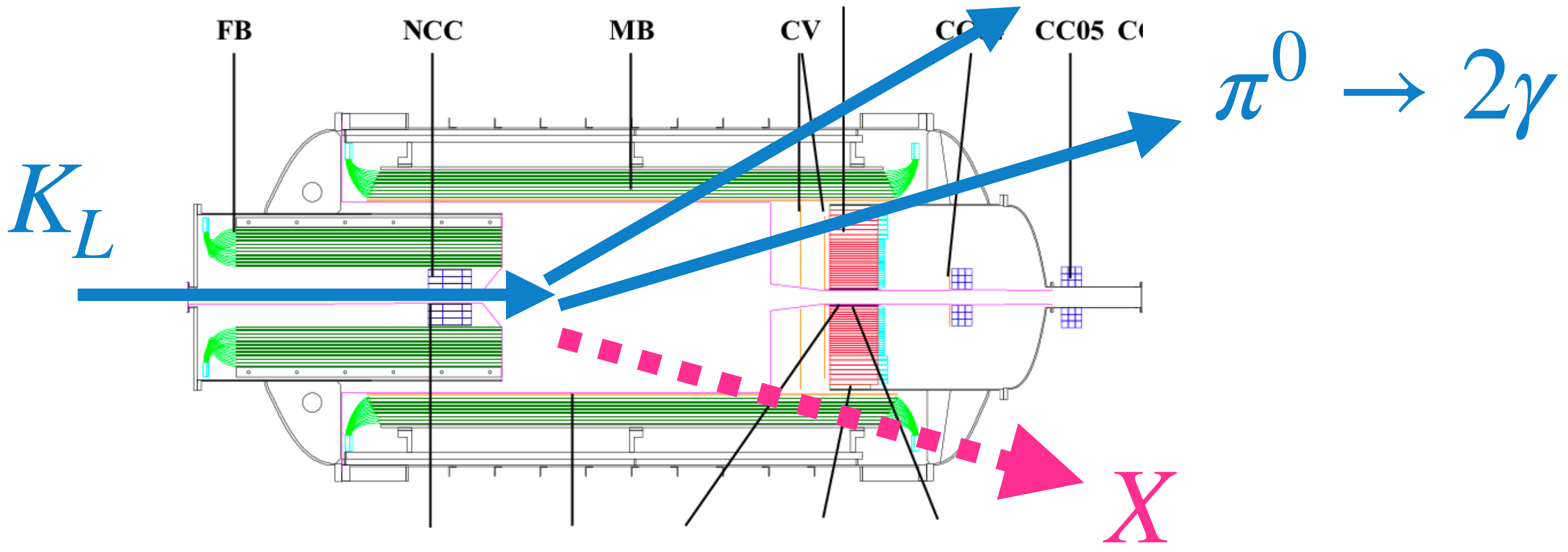
- New particle X (CP even) decays into $\gamma\gamma$ (or e^+e^-) with finite lifetime

[TK, Okui, Perez, Soreq, Tobioka ’20; Liu, McGinnis, Wagner, Wang ’20; Liao, Wang, Yao, Zhang ’20]



$K^+ \to \pi^+ X$, $X \to \gamma\gamma$ is rejected in the NA62 detector

L = 150 m, E = 37 GeV



X seems long-lived in the KOTO detector

L = 3 m, E ~ 1.5 GeV

Effective violation of GN bound “lifetime gap”

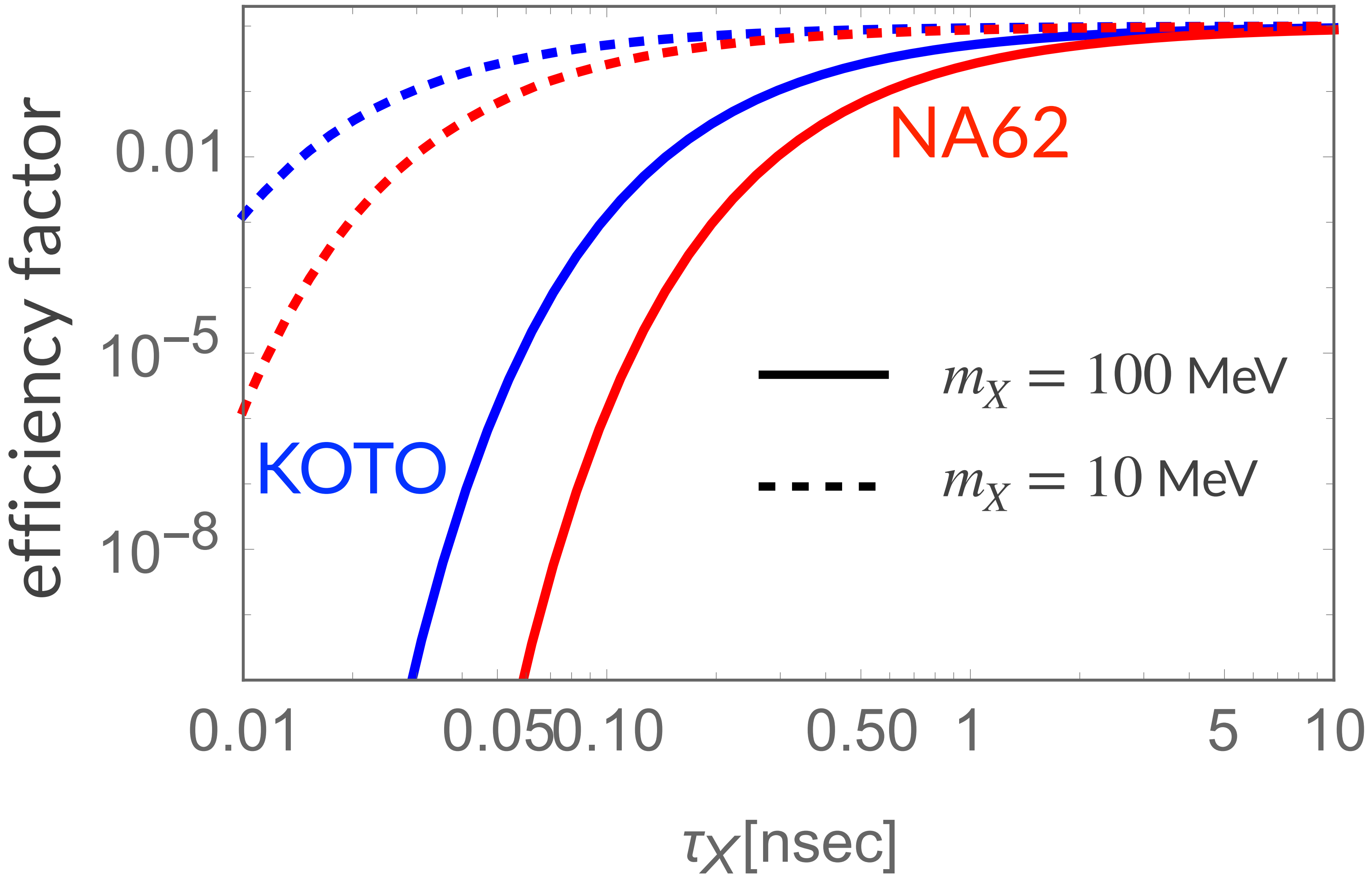
◆ Probability that *X* does not decay in the detector volume

= efficiency factor that *X* looks missing neutrinos

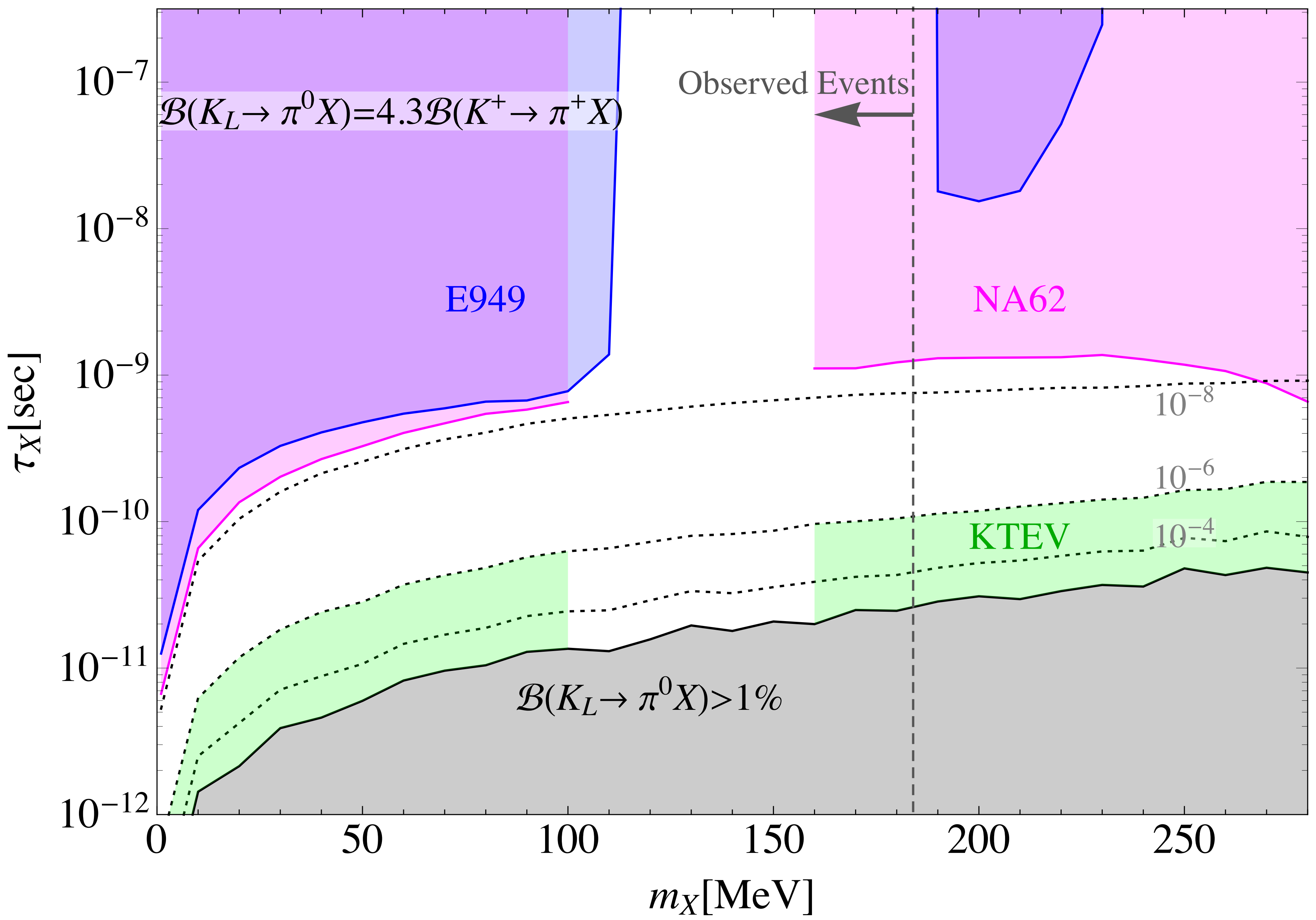
$$(\text{Energy scale})^2 \gg m_X^2$$

$$P = \exp(-\frac{L}{\gamma\beta\tau_X}) = \exp(-\frac{L}{(E_X/m_X)\beta\tau_X}) \simeq \exp(-\frac{Lm_X}{p_X\tau_X})$$

Efficiency difference
=
Effective violation of the GN bound



<Assuming 3 KOTO signals>



Comments

- <3 KOTO signals> are assumed in many plots. Now, this assumption should be changed.
- We should take special care to the KTEV/NA48 data of BR$(K_L \to \pi^0\gamma\gamma)$ which are consistent with SM prediction and new particle X must decay there [Liao, Wang, Yao, Zhang '20]
- FASER could probe the finite lifetime particle X via $pp \to K_L \to X \to \gamma\gamma$ [Kling, Trojanowski '20]. But, it is unclear that FASER can detect the diphoton signals
- Connection to muon g-2 anomaly is possible [Liu, McGinnis, Wagner, Wang '20]

Backup slide

Violation of Grossman-Nir bound by isospin-violating operators

Violation of Grossman-Nir bound by kinematics

Effective violation of Grossman-Nir bound by pion-mass new physics

Isospin-violating operators; other examples

- Isospin-violating axion operator = dimension 8

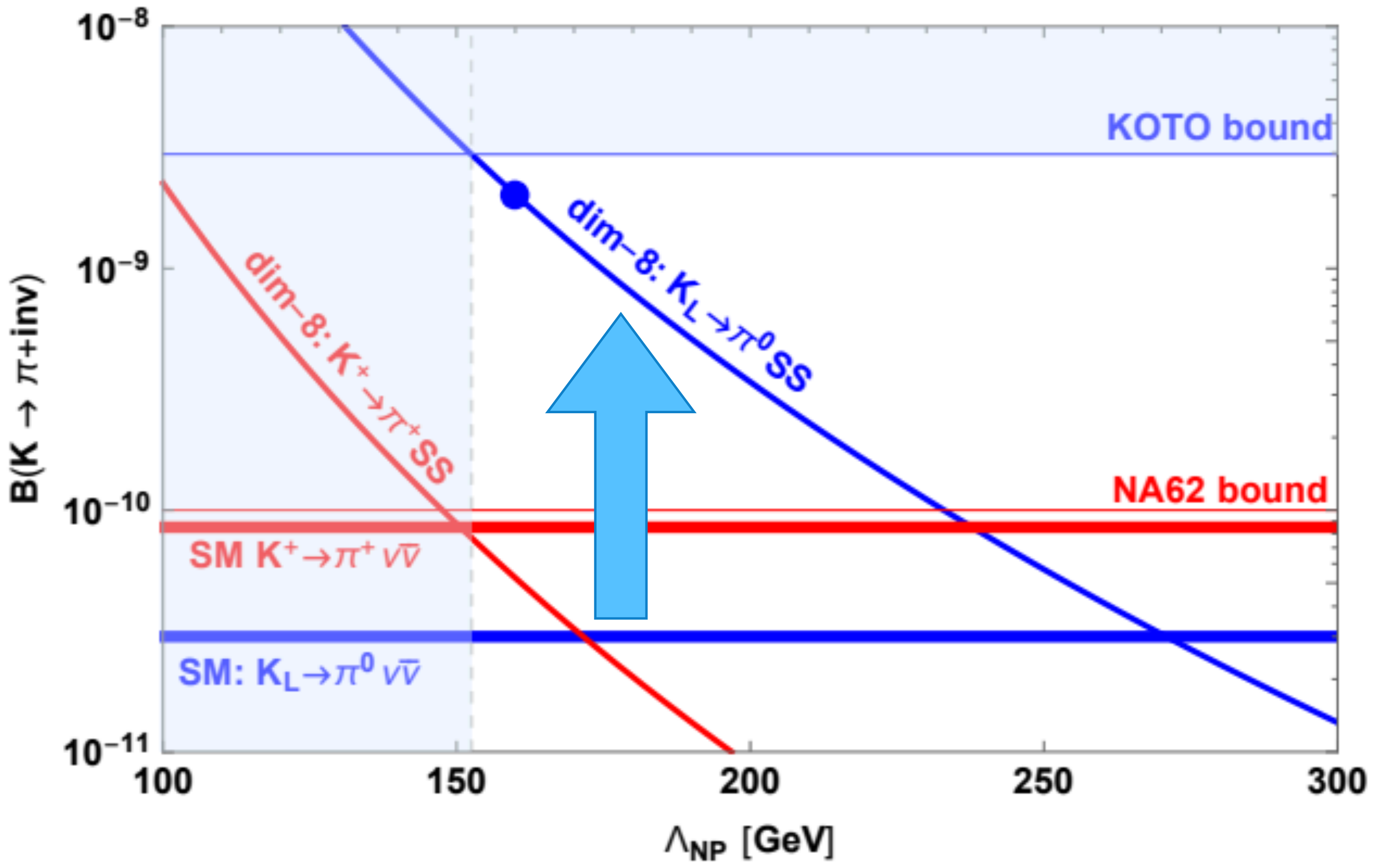
[TK, Okui, Perez, Soreq, Tobioka ’20]

$$\mathcal{L} = \frac{1}{\Lambda^4}\partial_\mu a(\bar{s}\gamma^\mu d)(\bar{u}u - \bar{d}d)$$

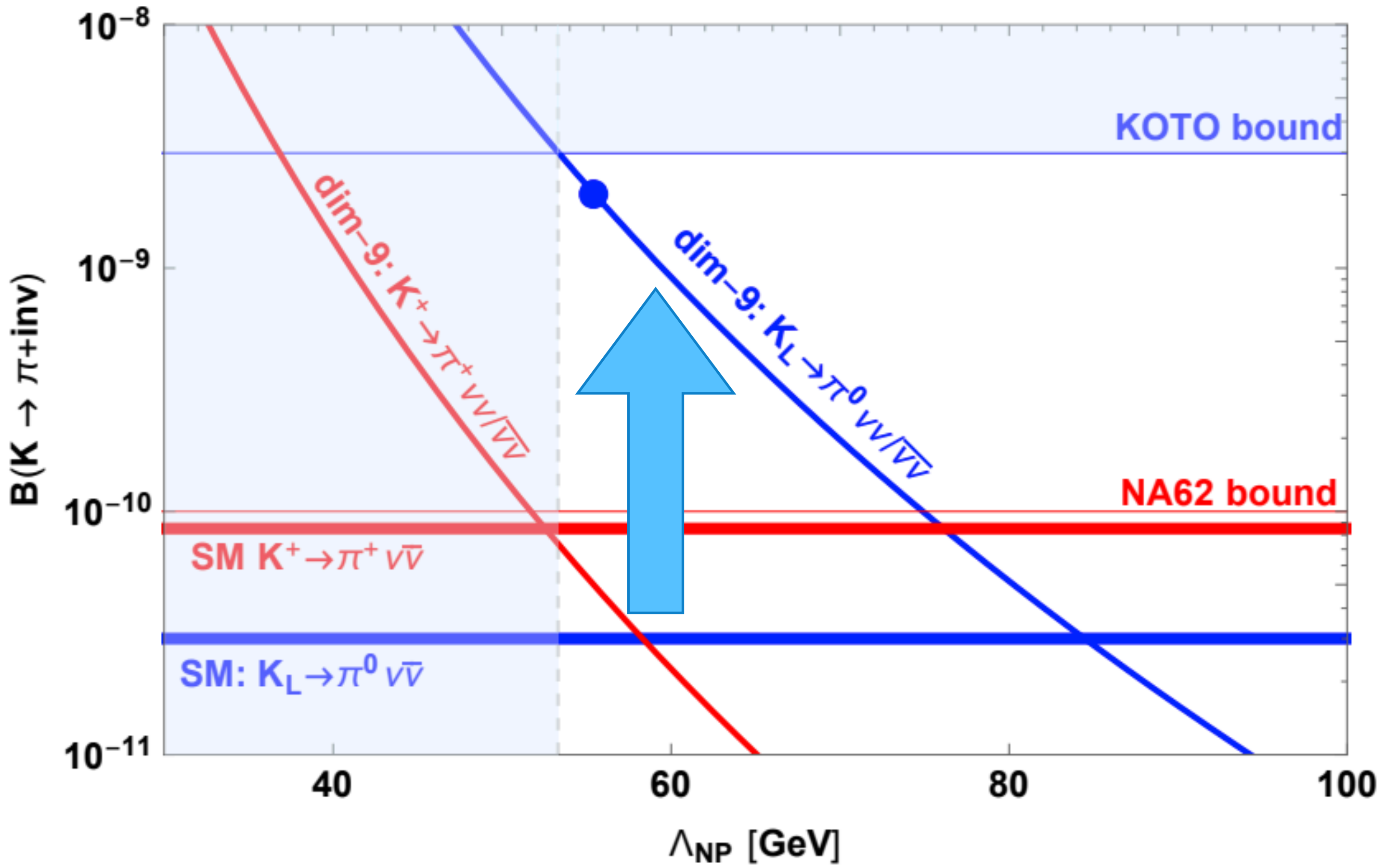
No study. But, dimension-5 axion operator is already severely constrained

- Other operators [He, Ma, Tandean, Valencia ’20, ’20]

$(\bar{s}d)(\bar{q}q)\, S^2$: dimension-8



$(\bar{s}d)(\bar{q}q)(\bar{\nu}^c\nu)$: LNV dimension-9



Note: $(\bar{s}d)(\bar{q}q)(\bar{\nu}\nu)$ enters from dimension-10

By kinematics

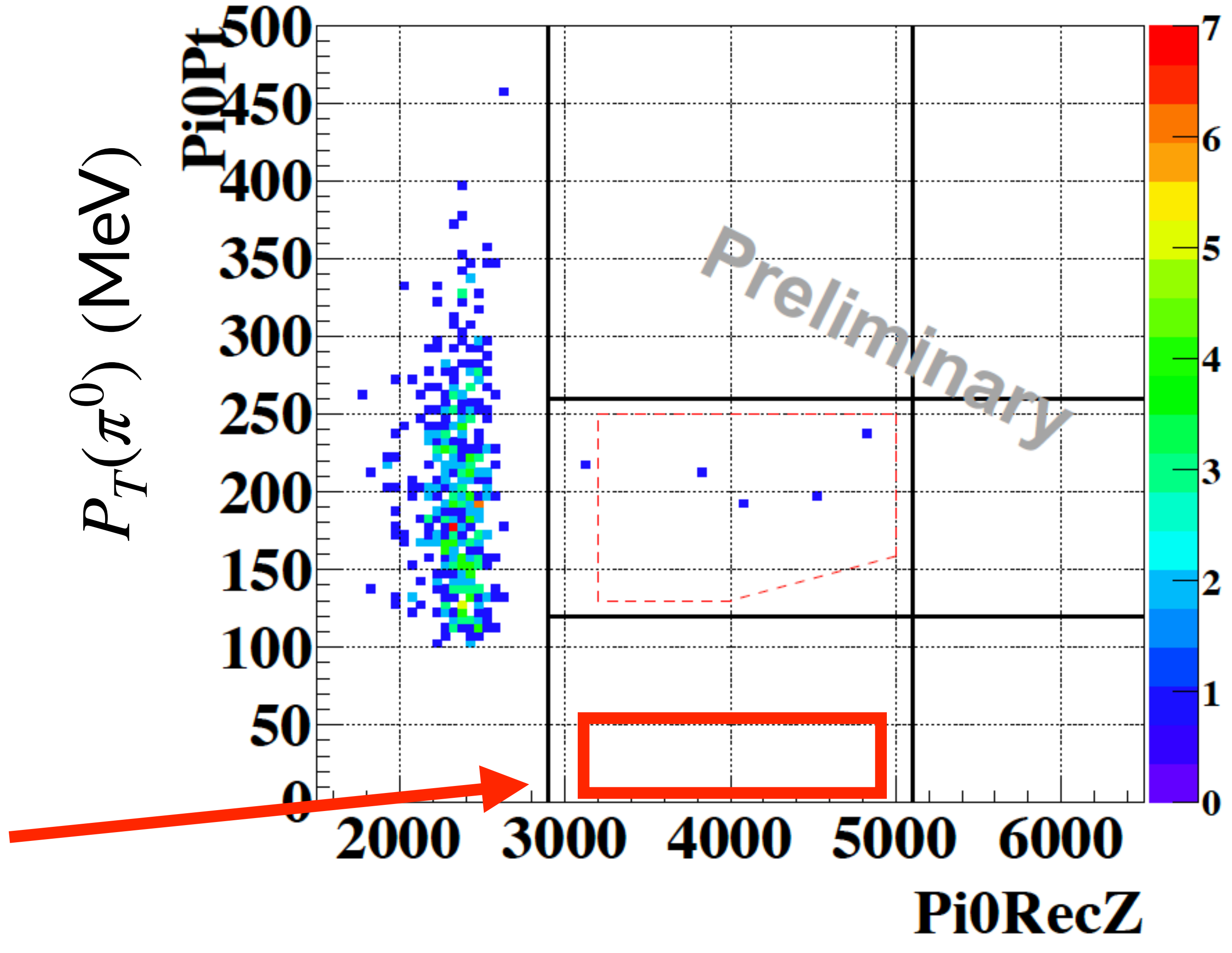
- Simple idea: violating the Grossman-Nir bound is just kinematics:

$m_{K_L} = 497.6$ MeV $m_{\pi^0} = 134.9$ MeV $\Delta m = 362.7$ MeV

$m_{K^\pm} = 493.6$ MeV $m_{\pi^\pm} = 139.5$ MeV $\Delta m = 354.1$ MeV

(Mass difference comes from the radiative corrections within the SM)

- $K_L \to \pi^0$ has a larger phase space than $K^+ \to \pi^+$
- Can new 360 MeV particle explain signals? → Impossible
- Emitted π^0 is too soft, the missing pT can not become large

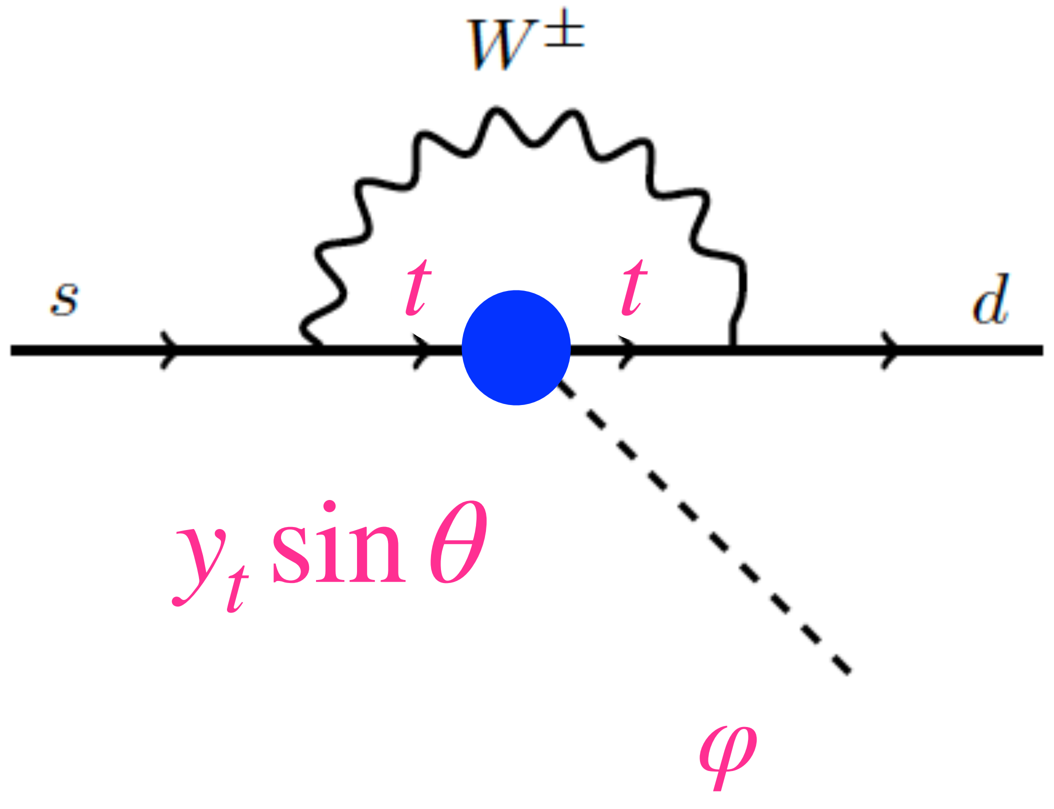


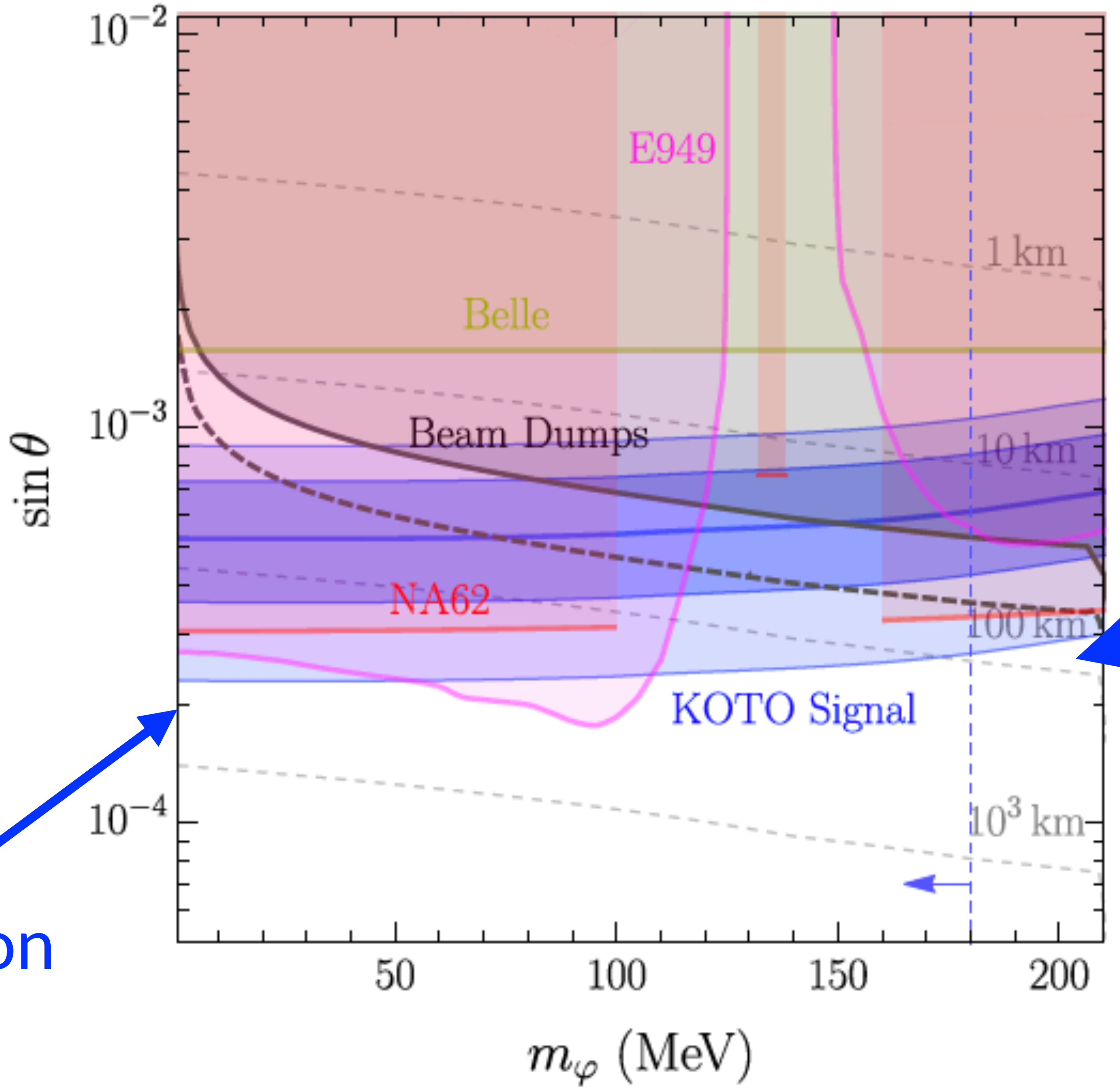
Predicted signal region [Fabbrichesi, Gabrielli '20]

Pion-mass new physics: minimal Higgs portal

[Egana-Ugrinovic, Homiller, Meade ’20, Bhupal Dev, Mohapatra, Zhang ’20]

◆ SM + light CP-even scalar φ, which mixes with the SM Higgs by $\sin\theta$





2σ statistical fluctuation

Dashed-gray contour: $c\tau_\varphi$,

φ is stable within detectors

BR$(\varphi \to ee) \sim 100\,\%$

“π^0 blind spot”

The constraint from $K^+ \to \pi^+ \nu\bar{\nu}$ is significantly loosened by the background of $K^+ \to \pi^+ \pi^0$

[Fuyuto, Hou, Kohda ’15]